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HOW WE PROCESSED APOLLO LUNAR SEISMIC DATA¹

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Abstract

The Apollo lunar seismic station network gathered data continuously at a rate of 3×10^8 bits per day for nearly eight years until the termination in September, 1977. The data were processed and analyzed using a PDP-15 minicomputer. On the average, 1500 long-period seismic events were detected yearly. Automatic event detection and identification schemes proved unsuccessful because of occasional high noise levels and, above all, the risk of overlooking unusual natural events. The processing procedures we finally settled on consist of first plotting all the data on a compressed time scale, visually picking events from the plots, transferring event data to separate sets of tapes and performing detailed analyses using the latter. Many problems remain especially for automatically processing extraterrestrial seismic signals.

1. Introduction

This paper was written not as a report of scientific results, but rather to describe the particular methods of digital data-handling which we developed during the course of the Apollo Passive Seismic Experiment.

Digital data acquisition, processing and analysis of seismic signals are now of common practice in such areas as oil exploration. However, fully digital operation of seismic network stations is a relatively recent development, and many problems still remain to be worked out. We were faced with all of these problems at once when the first seismic data started to come down from the moon in 1969, and have been trying to solve them ever since. The data flow lasted continuously for nearly eight years until all the then active ALSEP (Apollo Lunar Surface Experiment Package) stations were turned off on 30 September, 1977.

Our main concern in processing the data has been in achieving efficiency as high as possible within limited resources and without sacrificing the quality of the data, so that we can devote as much effort as possible to the analysis and interpretation of the data. Yet, more than half of our personnel resources, including significant amount of scientists' time, have been occupied in processing of the large quantity of data from these seismic stations on the moon. Faced with many unique data processing requirements, various new approaches were necessary.

The purpose of this paper, therefore, is to document this unique seismic data processing operation and associated problems. It is intended both (1) for potential as well as current users of the processed lunar seismic data, who may be interested in how these available data have been generated, and (2) for those who are involved in digital acquisition, processing and analysis of seismic network data (terrestrial as well as extra_{terrestrial}), who are interested in design of the data processing scheme.

In the following sections, we first describe briefly the data to be processed, and then describe in detail how we processed these data together with the reasons for adopting certain procedures. We will then discuss various problems associated with automatic processing of seismic data.

2. Data and Processing

2.1 Apollo Lunar Seismic Data

The Apollo lunar seismic network was established as a part of the Apollo lunar landing missions accomplished between 1969 and 1972. Each station contains a single-component, short-period ($T_0 = 1$ sec) and three-component, long-period ($T_0 = 15$ sec) seismometers (Latham, et al., 1969). In addition to the direct output signals from these four components, the feedback voltages used to stabilize each of the long-period instruments were also available as tidal output signals, which measure ground acceleration below 0.01 Hz.

These signals were continuously digitized at the station, and the entire digital data stream was transmitted to the earth in real time. No data compression or pre-selection of data to reduce the number of data bits to be transmitted were employed. Though this scheme required a large number of data bits to be transmitted, it also gave us ample opportunity to try out various event-detection and identification schemes on real lunar data in our own laboratory; such options were precluded by the data compression scheme of seismic experiment on Mars (Anderson, et al., 1977).

Sampling intervals for signal digitization were approximately 19 msec, 151 msec and 1.2 sec for the short-period, the long-period and the tidal components, respectively. Each data word contained 10 bits (60 db dynamic range). For the seven channels of seismic data described above plus the instrument temperature sampled at the same rate as the tidal data, each station generated a total of approximately 66 million bits of seismic information every day of operation.

Table I lists the duration of time each lunar seismic station was active and the cumulative years of activity. Of the five lunar seismic stations, all but the Apollo 11 station functioned up until the end of September 1977, when all of them were turned off by commands from the earth. The total number of bits generated and recorded in the 26.18 active station-years amounted to approximately 6.3×10^{11} bits. Storage of the entire data set requires more than

10,000 digital tapes at 800 bpi (bits per inch) density.

2.2 Data Processing

Because of the large quantity of data to be handled, the processing of these data turned out to be more than a routine task. The idea of producing conventional daily seismograms, familiar to most seismologists, was abandoned after a short trial for several reasons. Among them were a requirement for a larger computer hardware capacity than that available to us, more complicated software development compared with alternatives, and long processing time, which required more computer operators than we could afford.

As we mentioned earlier, the unabridged data transmitted from the moon gave us opportunities to try various automatic schemes for event detection and identification. These might have reduced the vast amount of data into more easily manageable size. Early trials included variable threshold detection, which selected only those signals which exceeded the average background noise amplitude by a pre-set factor, and cross-correlation of events which identified those events of similar temporal amplitude variations. However, neither of these techniques proved satisfactory. They were found either unreliable or too time consuming. A serious problem among others was the risk of not detecting some unusual natural events. Initially we were dealing with signals of completely unknown characteristics, and even after several different types of natural

seismic events were identified, there existed the possibility of finding still other types of events.

The laboratory data processing scheme we finally settled on is diagrammed in Fig. 1. Prior to receipt at our laboratory, the seismic data digitized at each of the seismic stations on the moon were multiplexed with other experimental and engineering data, and transmitted to earth in frequency modulated, pulse coded modulation (PCM). These real-time signals are recorded on analog magnetic tapes at range stations (receiving stations) located around the world to provide around-the-clock, line-of-sight coverage. The recorded tapes were then sent to our laboratory in Galveston for processing.

The routine processing of the data in our laboratory is performed in six steps as diagrammed. The digital processing is done using a PDP-15 mini-computer dedicated to this purpose. Because of a large initial backlog caused by the equipment setup and the unavoidable time delays between steps, we have completed to date only the first two steps for the final data of September 1977.

The first step of processing is to translate the PCM signals to computer-compatible digital signals. This step involves multiplexing asynchronous data from several lunar stations recorded on separate tape tracks. PCM decommutators and buffer memories controlled by combined PDP-11/PDP-15 minicomputers are used, achieving a processing speed normally 16 times real time. This step produces digital "work

tapes" that contain all the scientific and engineering data from all of the ALSEP stations. (Prior to March 1976, this first step was performed at the NASA Johnson Space Center.)

In the second step of processing, the first seismograms are produced from the work tapes in a greatly compressed time scale of approximately 75 mm/hr. Fig. 2 shows a sample compressed seismogram. The data are sufficiently compressed that one day's record from all the seismic stations can be plotted in parallel on a chart 28 cm wide and 180 cm long. The plots are produced on a matrix electrostatic printer/plotter, producing five-station seismograms at a processing speed approximately 27 times real time. The advantage of employing this step over other possible alternatives for producing the initial seismograms is the relatively high speed of generating useful seismograms for the entire network, essentially retaining all the information necessary for visual detection and initial classification of seismic signals. The plot compresses long-period signals by a factor of 80 in time with respect to the original data, reducing the timing accuracy to about 12 seconds. Thus only those seismic signals which last less than 12 seconds are lost during the compression process.

The third step is to visually inspect the compressed plots and to pick out all the seismic events recorded on any of the long-period instruments. This step allows us to look at the entire seismic data, thus enabling us to identify any seismic events of unusual interest.

Appearance, on the compressed plot, of signals of similar characteristics at two or more stations sometimes helps one to identify seismic signals. The arrival times, and amplitudes of all of the detected events are read and are entered into an event log together with any additional comments on the observations.

In the next step, the event log entries are punched on computer cards, using one card per event. This step thus generates the initial event card catalog. Later, the card catalog is updated following identification and classification of events based on analysis of expanded plots.

In step 5, the initial event cards control the data selection from the original work tapes to produce "event tapes", which contain only those portions of the seismic data which contain events. This step reduces the quantity of data tape to be handled in later analysis by a factor of about ten.

The final step of the routine processing is to produce seismograms for the first 10 minutes of each event in an expanded time scale, taking the data from the event tapes. The time scale of these seismograms is approximately 100 mm/min., and the amplitude scale is normally about 2 mm/DU, where DU (digital unit) is the amplitude corresponding to the unit digitization step. The latter corresponds to a magnification (trace amplitude divided by ground displacement) of about 30 million at the peak sensitivity of each lunar seismometer. At this time scale, all data words from the

long-period seismometers can be plotted, but an eight-to-one time-axis compression of the short-period data is required.

This completes the initial data processing. Most data analyses are then performed using the products of the last three steps of the processing.

2.3 Catalogued Events

In total, approximately 12,000 long-period events have been detected and catalogued during the slightly less than eight years of seismic station operation on the moon (Nakamura, et al., 1978). This number does not include seismic events detected by the short-period instrument only. These are much more numerous, and represent thermal moonquakes (Duennebier and Sutton, 1974a) and small, near-distance meteoroid impacts (Duennebier and Sutton, 1974b).

Table II gives the breakdown of the catalogued events by types. In addition to the 9 artificial impacts of man-made objects, consisting of spacecraft boosters and lunar landing modules (e.g. Latham et al., 1970; Toksöz et al., 1972), three kinds of natural teleseismic events have been identified. They are meteoroid impacts (e.g. Duennebier et al., 1975; Dorman et al., 1978), shallow moonquakes (Nakamura et al., 1974; Nakamura, 1977), which are now believed to occur just below the crust/mantle boundary (Nakamura and Koyama, 1978), and deep moonquakes (e.g. Latham et al., 1971; Lammlein et al., 1974), which occur about half way towards the center of the moon. To date about 9% of the total detected events

have been analyzed in detail, and the rest remain to be analyzed.

3. Discussion

We are now approaching the completion of the initial processing of the Apollo lunar seismic data. Reflecting on how we have processed this vast amount of digital data, we are reminded of the many problems we have faced during the past decade. A group of problems are associated with the simple fact of handling any large quantity of digital data, while another group of problems are associated specifically with our attempt to automate the processing of lunar seismic data. We will next review some of these problems in more detail.

Some of the problems associated with handling a large quantity of digital data are especially important in an academic environment, where both financial and personnel resources are quite limited. We simply cannot afford to employ processing schemes that tax the capacity of the relatively small computer systems available, thus necessitating additional computer operators and at the same time leaving little computer time for scientific data analysis. Thus, the efficiency of data processing has been one of the prime concerns to us. We have made several improvements in this respect during the course of this processing. By far the most significant (better than an order of magnitude) improvement in processing efficiency was achieved by employing a matrix electrostatic plotter in place of an incremental pen plotter for producing seismograms,

and by revising computer programs with efficiency in mind, including a switch to assembler language from Fortran.

Finding a competent computer programmer to write all of the necessary processing programs is another problem in the academic environment. Very few professional programmers understand scientific requirements sufficiently to write useful programs. Some scientists can write efficient data processing programs, but their efforts are not generally appreciated in the scientific community, and worse yet, time-consuming programming efforts often interfere with their academic achievements.

Another problem in handling a large quantity of digital data is the large volume required for storage. We have accumulated more than 11,000 digital magnetic tapes containing lunar seismic data, which now occupy about 50 m^2 of floor space in storage. Furthermore, data on magnetic tapes deteriorate with time. New techniques for higher density and more stable storage of digital information are definitely needed if we are to continue accumulation of digital data from seismic networks.

When faced with a very large quantity of data, the obvious first step is to attempt to find data compression schemes that retain all significant information while reducing the data set to a manageable level. Problems associated with this step are specific to a particular data set. For seismic data, the sections of data that are of main interest to us are those time intervals when

seismic signals, generated by discrete events, are present.

Other sections of the data can be deleted without significant loss. Thus arises the need for automatic detection of events. As discussed earlier, we have tried this with the lunar data without success.

Causes for the failure are several fold. First is the problem of noise, which makes event detection less reliable. Seismic noise on the lunar surface is caused mainly by thermal effects on the ground, on articles left by the astronauts, and in the seismic station itself. Additional noise is introduced in the long-range transmission of data. These noise sources cannot be eliminated. A second and more serious problem is the initially unknown characteristics of lunar seismic signals. If we assume certain characteristics for signals to be detected, we must accept the risk of not detecting signals which do not have the assumed characteristics. Thus, automatic seismic event detection for an unknown extra-terrestrial body is inherently risky. Finally, the great majority of the lunar seismic signals are very small, i.e., very close to the threshold of detection. This makes the automatic detection of signals extremely difficult.

Automatic classification of signals is another processing attempt which met with a failure. The great majority of lunar seismic events are believed to be deep moonquakes, but because of the very large number of these events, it is impossible to

identify and classify all of them manually. As a result, only a small portion of selected events have ever been classified (Table II). We have tried unsuccessfully to identify and classify these events by cross correlating amplitude variations with time. One of the reasons for the failure was again the noise problem. Additionally, processing time for this operation turned out to be prohibitively long for satisfactory identification of events.

For the more distant planets (e.g. Mars), the number of data bits that can be transmitted back to the earth is reduced greatly, and the problems of data selection and compression become increasingly important. Here we again face the necessity of assuming signal characteristics, of which we know nothing. Of particular importance is to find a proper data compression scheme. One of the data compression schemes used in the Viking martian seismic experiment samples amplitude and frequency of seismic signals every second. Phase information, which is lost in this compression scheme, however, may be significant. For example, we would have learned very little about deep moonquakes if the Apollo seismic data did not preserve the phase information of seismic signals. The problem of achieving efficient and useful data compression requires further, extensive study.

4. Concluding Remarks

The Apollo Passive Seismic Experiment gave us an excellent opportunity to work on a large quantity of digital data from a

network of lunar seismic stations. Though we have faced many problems, some of which are still unsolved, digital data offer many advantages in bulk processing and detailed analysis of seismic signals. Our unique experience in dealing with this set of data will be of great help to all of us for planning further seismic experiments of a similar nature.

Acknowledgements

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TABLE I

Active periods of Apollo lunar seismic stations.

ALSEP station	Active periods	Active years
Apollo 11	21 July 1969 - 27 Aug. 1969*	0.05
Apollo 12	19 Nov. 1969 - 30 Sept. 1977	7.87
Apollo 14	5 Feb. 1971 - 30 Sept. 1977	6.65
Apollo 15	31 July 1971 - 30 Sept. 1977	6.17
Apollo 16	22 Apr. 1972 - 30 Sept. 1977	5.44
Total Station-Years:		26.18

* Lunar daytime only

TABLE II

Catalogued long-period events.

Type	Analyzed in detail	Not yet analyzed	Total
Artificial Impacts	9	0	9
Meteoroid Impacts	~100	~1,600	~1,700
Shallow Moonquakes	28	0	28
Deep Moonquakes	~1,000	~1,800	~2,800
Unclassified		~7,500	~7,500
TOTAL:	~1,100	~10,900	~12,000

Figure Captions

Fig. 1. Block diagram of Apollo passive seismic experiment data processing.

Fig. 2. A sample compressed seismogram.

Data from four seismic stations (Apollo 12, 14, 15 and 16) and Apollo 17 station gravimeter (bottom trace), which functions as a short-period seismometer, are plotted simultaneously. This section contains signals from a shallow moonquake on 6 March, 1976. Small tick marks are at every 10 minutes.

PSE Data Processing Block Diagram

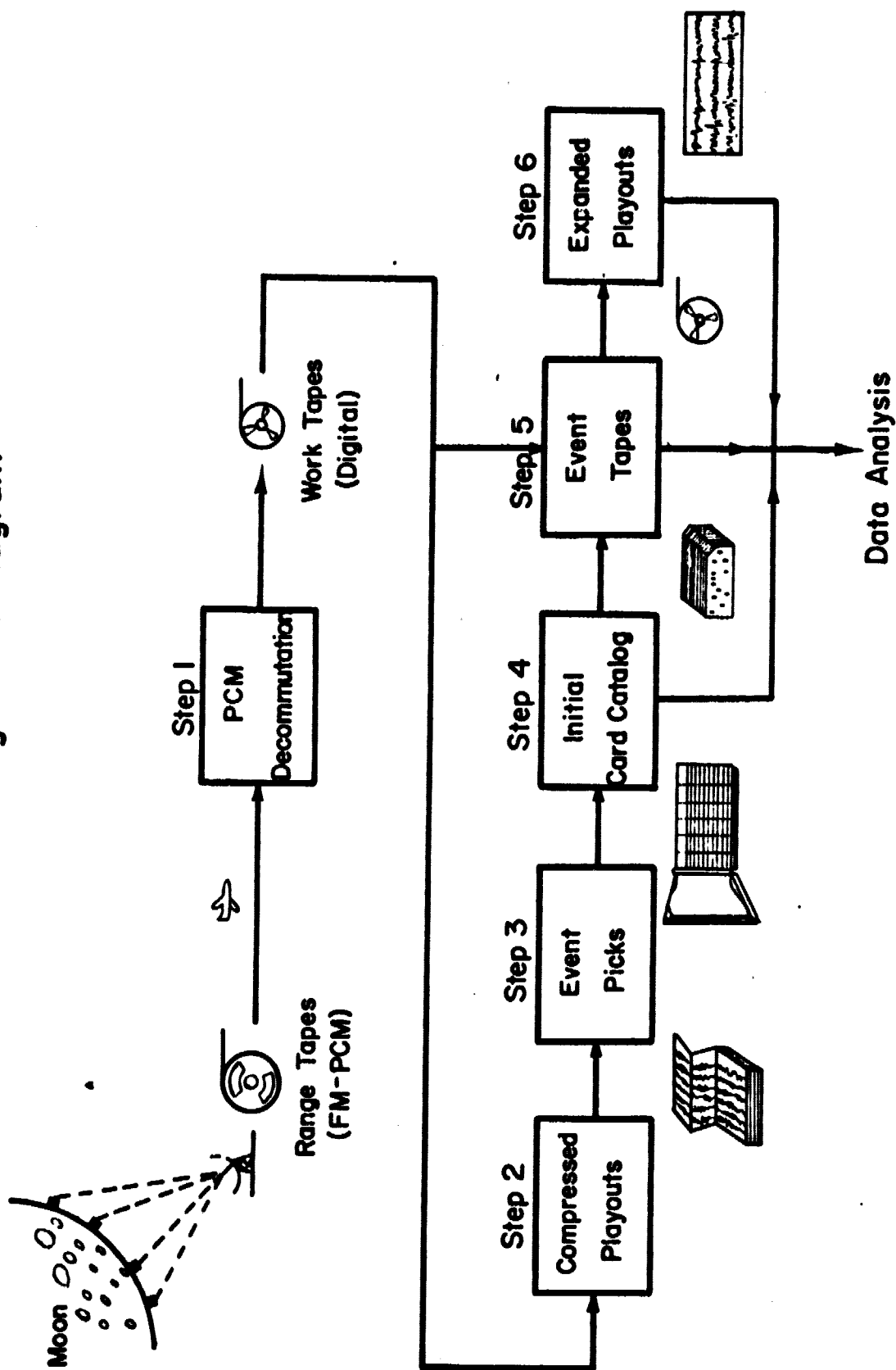


Fig. 1

TAPE ID = 15003 1976 DAY 66 1654

17 SPG I-----16-----15-----14-----13-----12-----11
SPZ LPZ LPY LPX SPZ LPZ LPY LPX SPZ LPZ LPY LPX SPZ LPZ LPY LPX

21

056/11

056/12